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# THE MULTIMATERIAL ARBITRARY LAGRANGIAN EULERIAN CODE MMALE AND ITS APPLICATION TO SOME PROBLEMS OF PENETRATION AND IMPACT

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## INTRODUCTION

In Lagrangian codes the Lagrangian mesh moves with the material velocity resulting in no need for the calculation of advection terms. Material boundaries remain on grid lines and the grid spans only the part of the space which is covered by the materials. These features make Lagrangian codes computationally much more efficient especially for multi-material calculations. However, as the grid distorts, both the accuracy and the efficiency of a Lagrangian calculation quickly deteriorates. Discrete or continuous rezoning is used to limit the grid distortion and keep the material boundaries smooth relative to typical cell dimensions. At material interfaces the tangential component of the material velocity may be discontinuous. Thus the grid may not remain continuous and a slide line treatment is needed to correctly handle the problem. Further, if different boundaries or different parts of a boundary, come into contact during the calculation, a sliding-impacting boundary calculation has to be performed to take into account the interaction of two separate grid regions. Apart from the coding complications which may soon become overwhelming, these techniques fail as soon as the material boundaries and interfaces become strongly distorted.

Eulerian codes, on the other hand, have coordinates that remain fixed in space. Thus Eulerian codes are best suited to dealing with problems producing large material deformations. However, in Eulerian coordinates one needs to compute the material advection through the mesh. Apart from the computational effort required, stability considerations require that these advection terms add at least some numerical diffusion and this may lead to severe smearing of the physical gradients present in the calculations. Another disadvantage of an Eulerian calculation is the need to cover, with the computational grid, any part of the space which may be reached by the material during the calculation. Together with the fact that in an Eulerian cell several materials may be present at the same time, this causes Eulerian codes to require much more computer memory to solve a given problem than Lagrangian codes, especially, if during a calculation, a thin layer of material should travel a distance many times its thickness. The main limitation of Eulerian codes, however, arises from the difficulty of adequately tracking the boundaries and interfaces. As a result of the above difficulties, successful numerical simulations of problems which involve large material

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deformations and impact of several materials may require a proper combination of Lagrangian and Eulerian techniques.

One method is to begin the calculation in a Lagrangian code and when the grid becomes sufficiently distorted to change, by a discrete rezoning, to an Eulerian code [1]. In the Coupled Eulerian Lagrangian technique (C.E.L.)[1,2,3] a special interface routine enables the interaction of Eulerian and Lagrangian regions. Apart from the complicated interface treatment, this method would fail if the Lagrangian regions should undergo large material deformations. An attractive alternative would be the use of convected coordinates [4,6].

In the original Arbitrary Lagrangain Eulerian (ALE) method [6,7,8] the grid motion could be arbitrarily specified but the material interfaces and boundaries had to be kept on grid lines. In the Eulerian limit the code would work only for one material application and this technique was thus equivalent to the continuous rezoning of a Lagrangian calculation. We shall call this an almost Lagrangian calculation. In a previous effort [4,5] we were able to remove some of the above restrictions. In the code LGTD free surfaces could cut the grid in an arbitrary way. We called this an almost Eulerian calculation. The method was applied to the numerical simulation of high speed jet penetration of layered targets. In those calculations the jet was simulated in an almost Eulerian grid, and the target was modeled in an almost Lagrangian way. Even a particulated jet [5] could be easily taken into account. However, the calculation failed as soon as the layers in the target were perforated by the jet.

In the present investigation we present a new, multimaterial, arbitrary Lagrangian-Eulerian code MMALE. It is a generalization of the code SALE [7] and it works in convected coordinates. As with Yaqui, [6,8] SALE [7] or LGTD [4,5] we may prescribe the grid motion in any arbitrary way. However, in MMALE both the free surfaces and the material interfaces can cut the grid lines. Thus, if we keep the grid fixed in space, we get an Eulerian multimaterial code, which will work in general coordinates, as a special case. However, even in the limit of a Cartesian-Eulerian grid, the code, as we shall describe it in chapter 2, has some endearing features.

By looking at the value of the relative partial volumes of different materials in neighboring cells we maintain a unique picture of the boundary lines cutting through the cell, thus reducing any interdiffusion of material properties. Each material in a mixed cell retains its velocity component so that sliding at interfaces should be correctly treated. When a given material flows out of a cell, we dynamically reallocate the released memory space, so that we essentially do not have to limit the number of materials interacting in a given region.

In contrast to pure Eulerian codes, we also take advantage of the freedom of prescribing the grid motion. Thus we may pass, in a continuous grid, from an almost Eulerian to an almost Lagrangian calculation while also reducing the advection term [5].

In the current work we apply the code MMALE to numerically simulate the penetration of a high speed copper jet into a metal-explosive-metal sandwich. The numerical simulation of the reactive flow induced in the explosive uses the Forest Fire model [9,10]. Both normal and $45^{0}$ oblique impact were considered.

## THEORY

Each time step is composed of a Lagrangian phase followed by an advection phase. SALE's Lagrangian step was essentially left unchanged except for the addition of elastic-plastic flow, the Forest Fire model

[9,10] for reactive flow and a multimaterial treatment. Thus, as in SALE, the Lagrangian step includes an implicit phase for low speed or almost incompressible flows. However, in the current application to high speed jet impact and penetration only the explicit phase was used. The treatment of elastic plastic flow uses the method of Wilkins [11] and our implementation is as in LGTD and LG1D [12,13].

## The Lagrangian Phase

In MMALE, different materials may share a given cell or a given vertex control volume. Thus, let M, ρ, V, e, p, and S be cell mass, density, volume, specific internal energy, pressure and deviatoric stress defined over a cell, and let $m_v, \vec{a}, \vec{u}$ be the vertex mass acceleration and velocity. We shall denote, with index k the respective partial values for a material k in a cell or at a vertex. For each material we retain w(k) = V(k)/V which is the relative partial volume occupied by k in a cell and we compute wv(k) which is the relative partial volume occupied by k in the vertex control volume.

We assume that for a given pressure gradient, each material k has acceleration proportional to the inverse of its density subject to the limitation of a common normal interface velocity and acceleration. The latter condition should prevent interpenetration of materials and allow for the correct sliding at an interface. The vertex total velocity is, according to momentum conservation, a mass weighted average of the specific velocities. The velocities determine the new cell volume. The relative partial volumes w(k) may change during the Lagrangian phase to equilibrate, on a physical time scale, the partial pressures in a cell.

We also allow for void opening under tension and void closure. Voids are taken into account as $w = \Sigma w(k) < V$, and we assume that under tension, if a failure criterion was met, any further volume increase will increase the void volume, thus decreasing w. The energy equation is then applied to each material k separately. The material model then yields, for each k, a new value of the partial pressure P(k) and stress S(k). The cell total pressure and stress deviator will be volume weighted averages of the partial values. Thus, $P = \Sigma w(k)P(k)$ and $S = \Sigma w(k)S(k)$ and these will be used to compute the new vertex accelerations.

## The Advection Phase

As in LGTD [4,5] we assume that the part of the boundary cutting a given cell is a straight line normal to ∇w(k). However, here we may have more than one material in a cell, and we proceed in the order of decreasing w(k). Thus given w(k) and ∇w(k) over a given polygon, we specify a unique straight line cutting that polygon. Thus the polygon not covered by the material k is now defined, and from the value of w(k) and ∇w(k) for the next material k, the next boundary line cutting the cell is determined. See Fig. 1. We advance, in time, the polygon covered by the material k, with the partial material velocities, $\vec{u}(k)$. The overlap of this polygon with the new grid determines the outflow flux volumes to the neighboring cells. With the condition that no increase in local gradients is due to the advection terms, we determine the flux volume centered densities by a volume weighted linear interpolation. Thus, we work with second order advection wherever this is permitted by stability.

As in SALE [7] the velocities are first averaged to cell centers to compute the advection terms. We chose to distribute the momentum flux to a given cell among its vertices, according to the fraction of the cell partial volume V(k), which lies inside the momentum control volume of a given vertex.

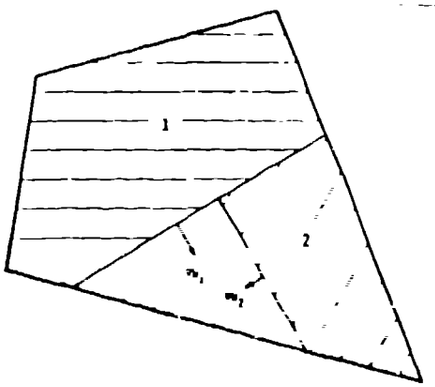


Figure 1. A typical computational cell showing the relative partial volumes of two materials and their gradients.

## Results and Conclusions

First, we consider the impact of a copper rod, 30 mm long and 4 mm in diameter moving at 4 mm/μs, upon a 5x6x6 mm, steel- Composition B- steel sandwich. For the case of normal impact, we run the code in an axisymmetric mode. We chose a cartesian Eulerian grid near the jet axis with a cell size of 0.5 mm. As we moved away from the axis we increased the size of the radial divisions passing gradually to an almost Lagrangian grid. In Fig. 2 we see the isobars and the material interfaces at times of 5 and 7.5 μs respectively. We see the buildup to detonation, followed by the

Figure 2. Normal impact. Times are 5 and 7.5 μs. Peak pressures (H in the figure) are 17 and 12 GPa respectively. Low pressure regions (L in the figure) are essentially zero pressure with 10% changes per iso-line.

radially outward propagation of the detonation front along the explosive with attached oblique shock waves generated in the steel layers. An interesting phenomenon occurred in the calculation near 7.5 μs, as a retonation wave swept back toward the axis, resulting in the complete burning of the partially reacted explosive remaining there. We notice that the pressure induced in the first metal layer, caused a significant decrease in the diameter of the hole created by the penetrating jet.

For the case of 45° oblique impact, we considerd a "sheet" jet and we ran the calculation in a plane symmetric mode. In this case the original grid was not orthogonal as the grid lines were parallel respectively to the jet and to the interfaces in the target. In Fig. 3 one can see the pressure field at times of 2 and 6 μs. In this case the lower part of

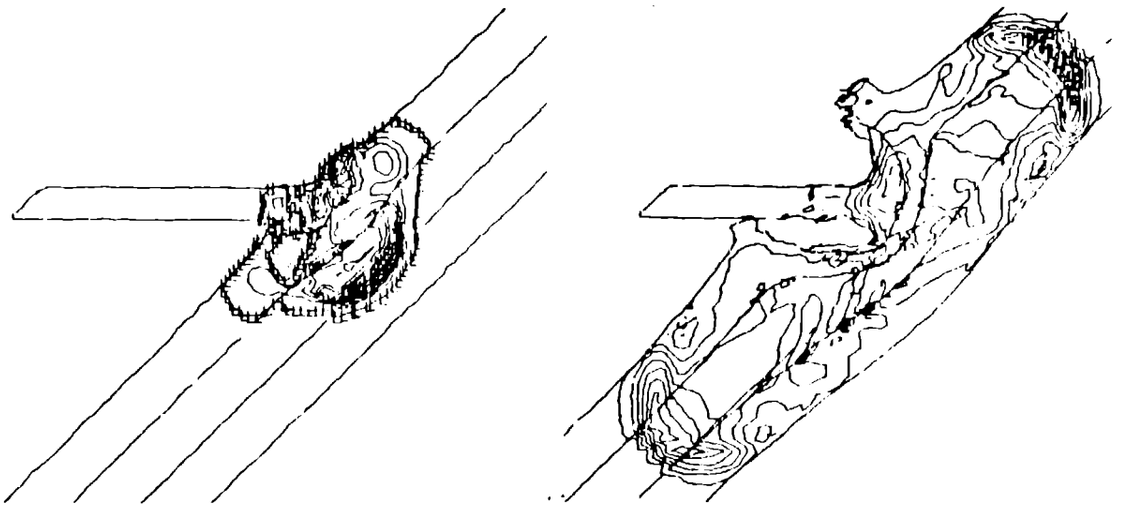

Figure 3. Oblique (45°) impact. Times are 2 and 6 μs. Peak pressures (H in the figure) are 30 GPa. Low pressure regions (L in the Figure) are essentially 0. Note the jet erosion at 6 μs caused by projection of steel into the jet's path.

the first steel layer was projected, by the detonation wave, toward the incoming jet. At first this caused a perturbation to grow in the jet. Later, the upper part of the second steel layer was also projected toward the jet axis. Thus, the penetration capability of any subsequent jet segment will be greatly reduced. The examples show the versatility of the current method. Obviously the advantage of our approach over a pure Eulerian or Lagrangian calculation depends on the specific application and on the appropriate choice of the grid motion.

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